10.4 Structural Safety

On July 1, 1940, the Tacoma Narrows Bridge, in Tacoma, Washington, was completed. On November 7, 1940, the main span of the bridge collapsed during winds of 64 km/h (**Figure 1**). The bridge was built to withstand winds of far greater speed. How could such a large structure, over 12 m wide and almost 1 km long, fall so easily? In this section, you will learn how the physics of waves can improve the safety of structures such as bridges and buildings.

WEB **LINK**

To see a video of the Tacoma Narrows Bridge during the high winds in 1940,

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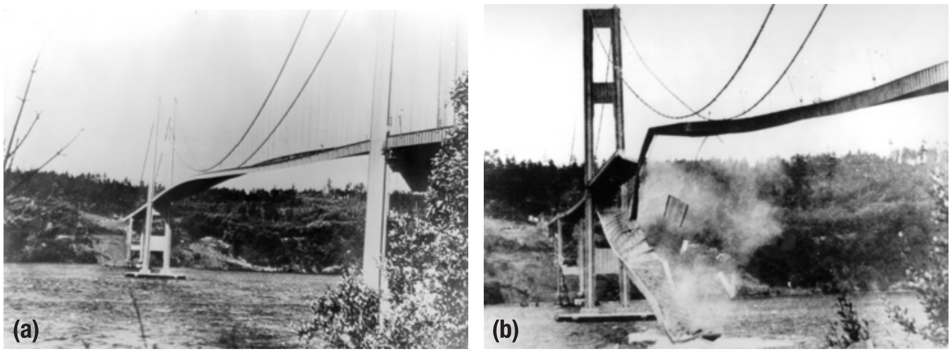

Figure 1 Physicists believe that waves had a lot to do with the collapse of the Tacoma Narrows Bridge in 1940. (a) The centre span of the Tacoma Narrows Bridge began vibrating because of the wind. (b) Eventually, built-up energy in the vibrations caused extremely large amplitudes, and the bridge collapsed under the strain.

Mechanisms Causing Vibrations

mechanical resonance the transfer of energy from one object to another, causing large-amplitude vibrations when the second object has the same resonant frequency as the first

In Section 9.4 you were introduced to resonance. **Mechanical resonance** occurs when there is a transfer of energy from one object to another with the same natural or resonant frequency. The child–swing system is an example of mechanical resonance, because there is physical contact between the periodic force applied (the source of the vibrations) and the vibrating object.

Consider the series of pendulums suspended from a taut string in **Figure 2**. When pendulum A is set to vibrate, pendulum E will also start to vibrate. As E gains amplitude, A loses amplitude. Eventually, E will develop large amplitudes and A will hardly move at all. During this time, the other pendulums will move slightly but never develop large amplitudes. The energy from A is transferred through the string to the other pendulums. However, only pendulum E, with the same natural frequency, begins to vibrate in resonance. This is called **sympathetic vibration**, and it occurs when one object vibrates in resonance with another of the same resonant frequency.

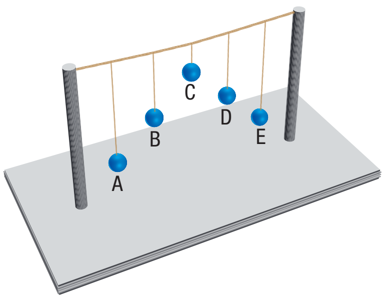

Figure 2 A series of pendulums can demonstrate sympathetic vibrations.

sympathetic vibration the response to a vibration with the same resonant frequency

aeroelastic flutter the response when the energy added to a structure vibrating in air exceeds the energy lost due to damping, causing large vibrations

Another mechanism that can cause objects in air to vibrate with large amplitudes is **aeroelastic flutter**. This happens when more energy is added to the vibrations than can be lost to the natural damping of the structure. It occurs when the wind exerts a force on a structure due to the aerodynamics of the structure. The elasticity of the structure allows it to vibrate.

There is significant disagreement among scientists on the primary cause of the collapse of the Tacoma Narrows Bridge. Physicists believe that mechanical resonance was the primary cause, but engineers believe that aeroelastic flutter was the primary cause. A generally accepted cause is that the wind transferred more energy to the bridge during each vibration than it could lose during the same vibration. This caused torsional vibrations: one side of the bridge moved up when the other moved down, with the centre of the bridge remaining at rest. Eventually, enough energy built up to cause extremely large amplitudes of vibration, and the bridge collapsed under the strain. Engineers now ensure that new structures can withstand wind speeds higher than the wind speeds possible in the area of the structure.

Vibrations in Buildings

Large vibrations in buildings can be caused by earthquakes. For most areas, however, they are caused by wind. Tall buildings constructed before World War II were built with concrete, which resists compressions well but is not very flexible. If a concrete skyscraper starts to sway, the concrete can crack and the building can fall. To prevent this, engineers strengthened the buildings with massive, thick walls. In addition, the engineers added steel bars, which can bend slightly, to the rigid concrete to improve flexibility. A good example of this type of construction is the Empire State Building in New York City (**Figure 3**). However, this method is very expensive, and as skyscrapers were made taller, engineers had to find new technologies to construct them.

After World War II, skyscrapers were built with a series of huge metal pillars (girders) that act as the frame for the building. The actual walls (called curtain walls) on the outside of the building are glass and act as weatherproofing rather than structural support. However, as more tall buildings go up in a small area, wind is forced into a relatively narrow street, causing an increase in wind speed. This occurs because the same amount of air must pass through a smaller space. Engineers must take this increase in wind speed into account when designing new buildings. They must also consider people walking at street level.

Wind can cause some skyscrapers to sway up to 1 m at the top floor. Earthquakes can cause vibrations with even greater amplitudes. To help decrease the amplitude of these vibrations due to resonance or aeroelastic flutter, some buildings have a mass damper, usually consisting of a pendulum made out of concrete or steel. These dampers develop sympathetic vibrations, which take energy from the building when it vibrates, thus decreasing its amplitude. The dampers are designed to take the energy before it can return to the building. Sky lobbies (horizontal areas), which break up the design of a structure at different altitudes, also help by decreasing the surface area of the tower at higher elevations (**Figure 4**). This reduces the forces caused by winds.

Figure 3 The Empire State Building in New York City was built using massive concrete walls to reduce vibrations.

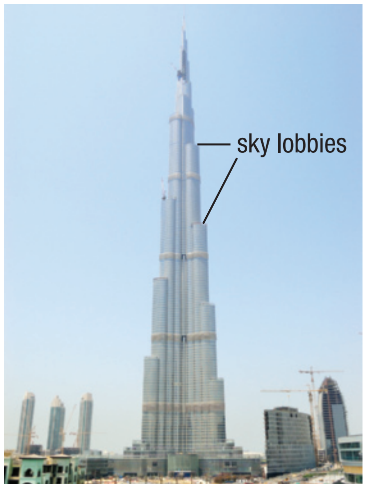

Figure 4 At 828 m, the Burj Khalifa, in Dubai, is the tallest structure ever built. Notice the sky lobbies in this structure.

10.4 Summary

- Mechanical waves can damage structures.
- Mechanical resonance occurs when a periodic force acts on an object at the natural or resonant frequency of the object. Mechanical resonance must be considered when designing structures and buildings.
- Aeroelastic flutter occurs when an object is vibrating in air and the input energy is greater than the energy lost due to damping.

10.4 Questions

1. Explain how you could apply the principles of mechanical resonance to a car when it is stuck in the snow. T/I A
2. When walking across a footbridge, some people notice that it moves up and down. One person suggests that they all march across the bridge together stomping their feet at the same time. Explain why this is a dangerous idea. T/I
3. If pendulum A in Figure 2 on page 464 starts swinging back and forth, then pendulum E will develop sympathetic vibrations. K/U T/I C
   (a) Explain why this happens.
   (b) What do you think will happen if pendulum E has a large amplitude swing?
   (c) As pendulum E gains amplitude, pendulum A loses amplitude. Explain why.
   (d) Describe how to use a beaker filled with water to make pendulum E into a mass damper similar to those found in some skyscrapers. Explain how it works.
4. Give two reasons why large concrete walls are no longer used when constructing skyscrapers. K/U
5. In a Venn diagram, compare and contrast mechanical resonance and aeroelastic flutter. K/U C
6. In your own words, describe why the Tacoma Narrows Bridge collapsed when the wind speed was only 64 km/h. K/U C
7. Research building safety. Find a technology not mentioned in this text that is used to reduce vibrations in buildings during windy conditions or during an earthquake. Determine the effectiveness of the technology. Write a short assessment of your findings. T/I C

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